Glenn Research Center

Jet Propulsion Laboratory
California Institute of Technology

High Power Demonstration of a 100 kW Nested Hall Thruster System

Sarah Shark
Aerojet Rocketdyne, Redmond, WA

Scott Hall
Vantage Partners, LLC, Cleveland OH

Benjamin Jorns
University of Michigan, Ann Arbor, MI

And

Richard Hofer and Dan Goebel
Jet Propulsion Laboratory, Pasadena, CA

AIAA Propulsion and Energy Forum
Indianapolis, Indiana
August 19-22, 2019

Agenda

- NextSTEP Program Requirements
- XR-100 Nested Hall Thruster System Overview
- XR-100 High Power System Test (HPST) Overview
- XR-100 HPST Results and Accomplishments
- Forward Work

NextSTEP Advanced Propulsion Systems

- Next <u>S</u>pace <u>T</u>echnologies for <u>E</u>xploration <u>P</u>artnerships
- Objectives: Advance the TRL of high power Electric Propulsion systems
  - 50 kW to 300 kW per thruster range
  - Test at a minimum system input power of 100 kW for 100 hours
  - Operate over broad power and specific impulse range
  - Scalable to MW
  - Extended lifetime and operational (thrusting) time
  - Manageable specific mass of total propulsion system
- 36 month effort with potential follow-on efforts for further technology maturation

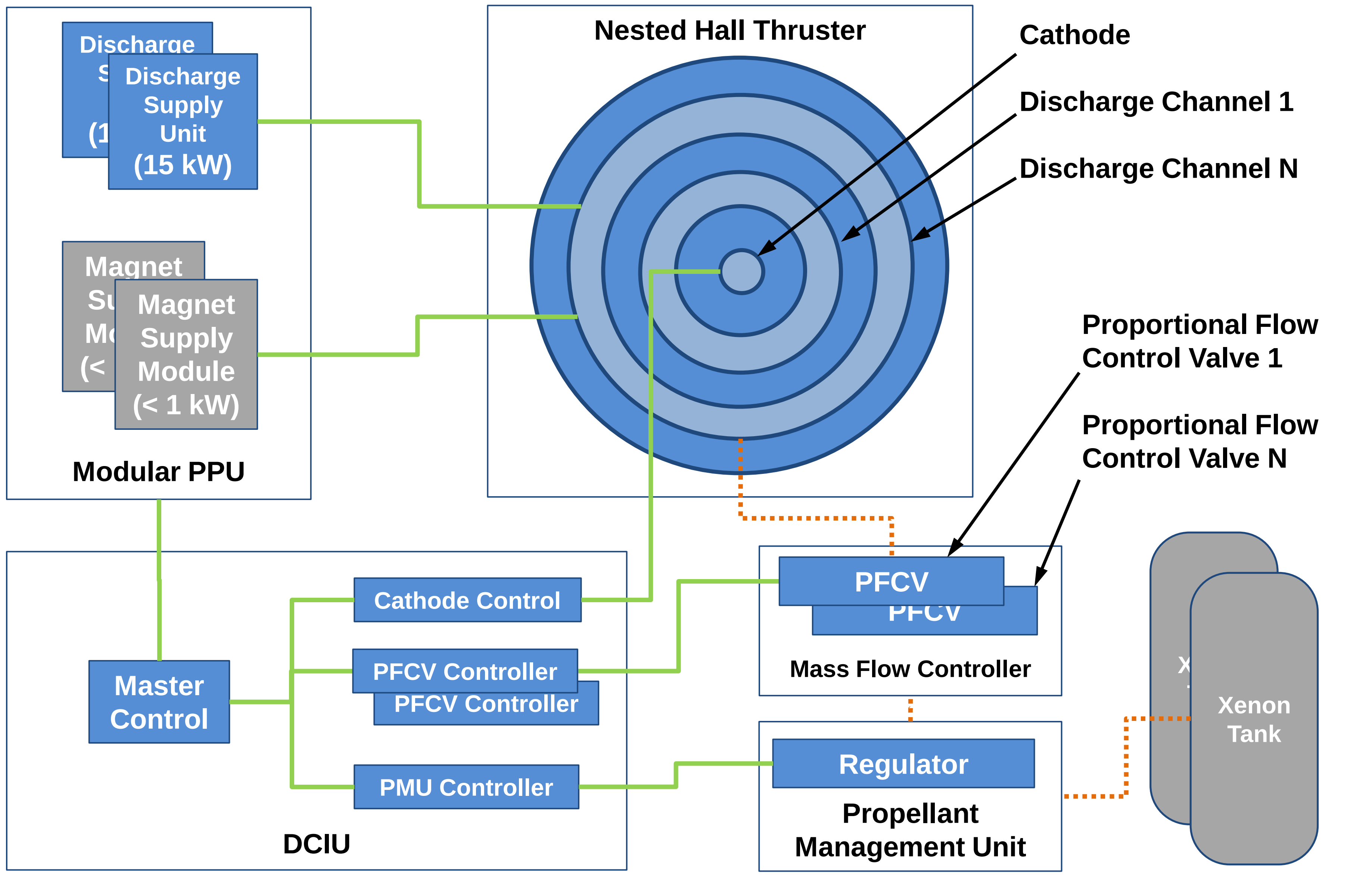
XR-100 Nested Hall Thruster Propulsion System

- XR-100 program is joint collaboration between Aerojet Rocketdyne (AR), NASA Glenn Research Center (GRC), University of Michigan (UofM), and NASA Jet Propulsion Laboratory (JPL)
- XR-100 is a 100 kW-class Hall Thruster propulsion system
  - Builds off of heritage technology, demonstrating capability to scale up to high power
- Performance Targets

Metric	XR-100 Design Goals
Specific Impulse	~2,000 to ~5,000 s
In-space lifetime capability	>50,000 h
Operational lifetime capability	>10,000 h
System efficiency	>60%
System kg/kW	<5 kg/kW

Block Diagram of XR-100

Blue blocks were under development as part of NextSTEP program



X3 Nested Hall Thruster (NHT)

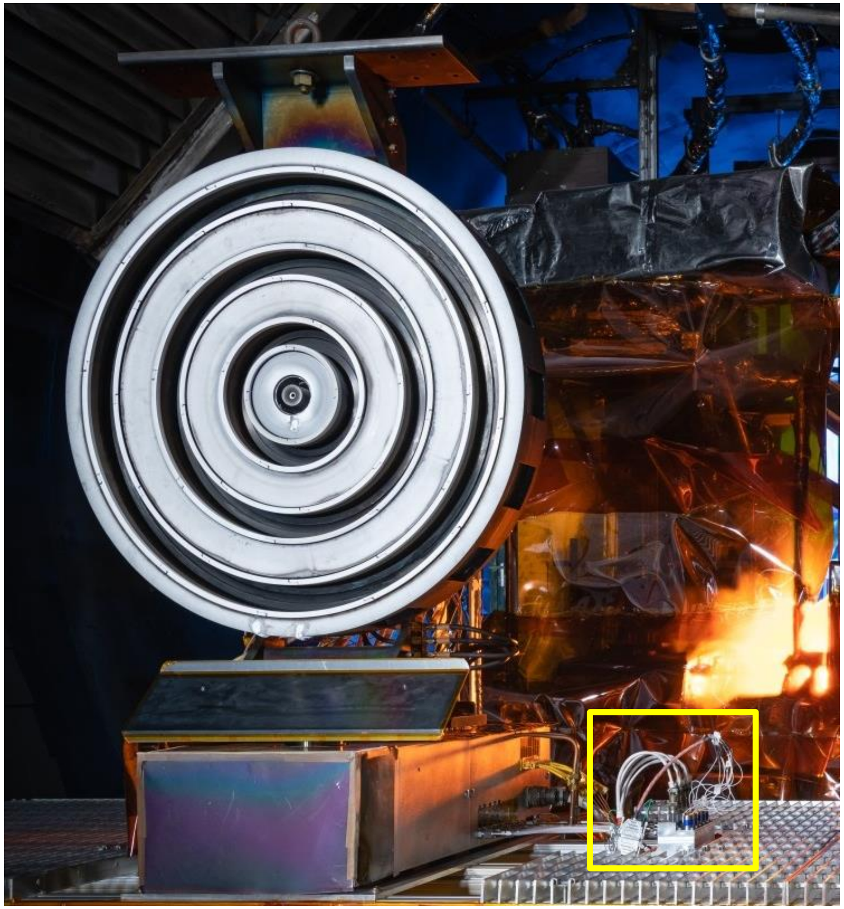
- UM developed the three-channel X3 NHT in collaboration with the AFRL, NASA GRC, and JPL
- Designed to 200+ kW
- X3, like other NHTs, scales up in power by adding discharge channels
- Each channel is independently controllable, enabling throttleability in thrust and power
- X3 design leverages extensive work on prior Hall thrusters.
  - X2 (UofM and AFRL)
  - H6 (JPL, AFRL and UofM)
  - NASA-457M, NASA-400M and NASA-300M
- X3 incorporates a 300A, LaB_6 hollow cathode developed by JPL

Power Processing Unit (PPU)

- AR-developed PPU builds on AR heritage and AEPS 13 kW PPU
- Modular design supports parallel configurations, independent power to each discharge channel
- Easily expandable to higher powers
- PPU consists of multiple Discharge Supply Units (DSUs) and a System Flow Controller (SFC)
- DSU made up of:
  - 4 Power Modules, Controllers
  - Input and Output Filters
  - Master Control Board
- DSUs can be operated for:
  - Maximum thrust at 350V-400V
  - Maximum Isp at 700V-800V

Mass Flow Controller (MFC)

- **AR-developed MFC based on AR proprietary designs**
- **Both the MFC and Propellant Management Unit (PMU) use a Proportional Flow Control Valve (PFCV) designed for low cost**
  - **Wide dimensional tolerances**
  - **No welding**
  - **No stroke or load adjustment required**
- **Each PFCV outlet has an integral PT for independent flow verification**
- **Modular design supports scaling to higher powers**



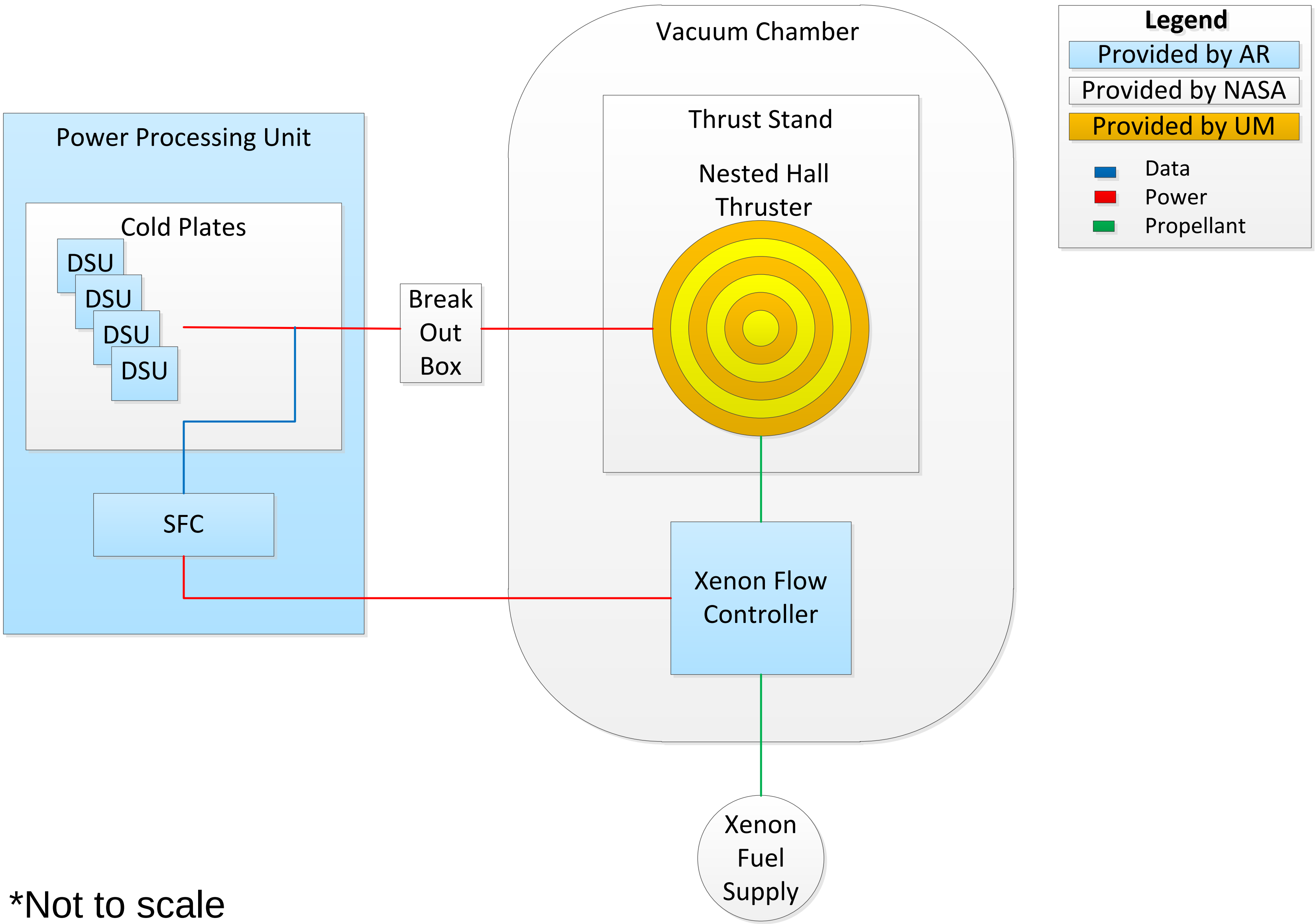
XR-100 Program Activities

- X3 Nested Hall Thruster testing up to 100 kW
  - Thruster and facility risk reduction
- XR-100 System Test at 10 kW
  - NHT, PPU, and MFC can operate together at 400 V and 800 V
- 45 kW PPU test
  - Validated multi-DSU master-slave control relationship
- High current LaB6 cathode development and testing
  - Modified design, demonstrated 300+A operation
- NHT and cathode plasma and thermal modeling
  - Drove design improvements
  - First-ever simulation of a Nested Hall Thruster
- XR-100 High Power System Test up to 100 kW

XR-100 High Power System Test (HPST)

- **Ultimate program objective for NextSTEP**
  - **Culmination of all previous risk reduction activities**
- **Performed at NASA GRC's Vacuum Facility 5 (VF-5)**
  - **700 kL/s pumping speed on xenon**
  - **Facility base pressures 1×10^{-7} Torr, max observed 6×10^{-5} Torr-Xe during 245 mg/s operation**
- **System test included:**
  - **UM's X3 NHT**
  - **AR's PPU**
    - **7 DSUs on cold plates**
    - **SFC**
  - **AR's MFC**
    - **5 PFCVs – one for each discharge channel, two for high current cathode**
  - **Thruster Heater, Keeper, and Magnets (HKM) run with lab power supplies**

XR-100 HPST Overview



*Not to scale

XR-100 HPST Overview

- **X3 NHT radiation cooled on thrust stand**
  - **JPL's LaB_6 hollow cathode**
- **MFC co-located with X3 NHT on metallic platform**
  - **Use existing Xenon flow system for upstream regulator, flow meter**
- **PPU outside VF-5**
  - **7 DSUs on cold plates in racks**
    - **Originally 1 DSU Inner, 2 DSUs Middle, 4 DSUs outer**
    - **Reconfigured to 3 DSUs Middle, 4 DSUs Outer**
    - **For three channel operation, ran Inner channel on 30 kW lab power supply**
  - **SFC next to Breakout Box (BoB)**

Test Equipment

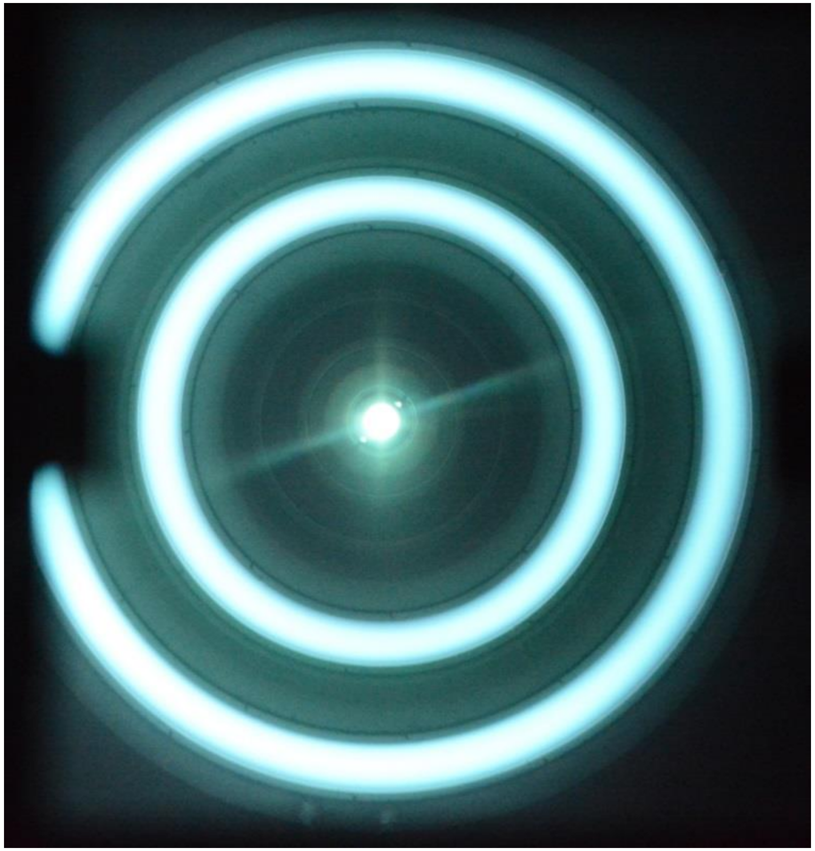
- Previously validated and demonstrated during NHT risk reduction testing up to 100 kW
- Inverted-pendulum thrust stand operated in null-mode
  - Based on UM X3 NHT thrust stand
  - Capable of measuring up to 8 N, with 0.8% uncertainty
- Thermocouples placed throughout thruster, magnet coil, MFC body, DSUs
- Low frequency data collected at 0.5 Hz
- High frequency data collected with three oscilloscopes, high speed current and voltage probes
- Total xenon flow measured by 2000-sccm commercial flow controller

Test Objectives

- **Demonstrate thermal equilibrium of the XR-100 system operating multiple NHT channels at >50 kW**
  - **First thermal equilibrium data to be collected**
  - **Help inform future design work**
  - **Validate technology can achieve stable and passively manageable thermal steady-state operation**
- **Demonstrate electrically stable three channel XR-100 system operation at >50 kW**
  - **Validate three channel system operation not uniquely different from two channel system operation**
- **Demonstrate XR-100 system operation at 100 kW system power for 100 hours**
  - **Final program objective for NextSTEP**
  - ***VF-5 pumps saturate prior to 100 continuous hours operation at high flow rates**

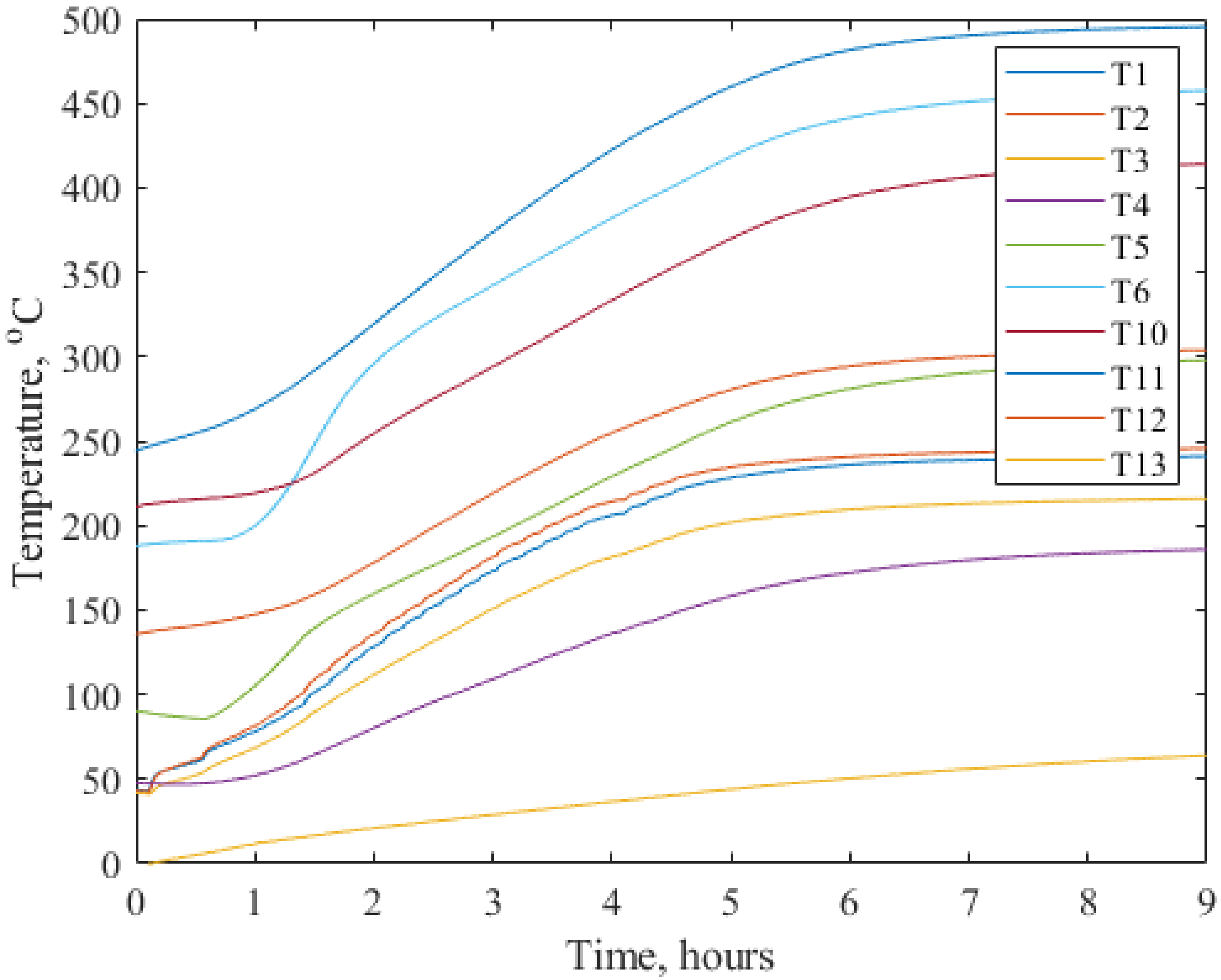
Two Channel XR-100 System Operation

- **XR-100 system successfully reached thermal equilibrium operating two channels at >50 kW**
  - **73.5 kW total power**
    - **300 V, 220 A discharge**
  - **Middle channel on 3 DSUs**
  - **Outer channel on 4 DSU**
  - **Following magnet bakeout and thruster conditioning**
- **Thermal equilibrium defined as temperature changes <1 ^{o}C/hour**
  - **Thruster reached thermal equilbrium within 6 hours at 73.5 kW**
  - **DSUs reached thermal equilibrium within 1 hour at 73.5 kW**
    - **Repeated during single DSU vacuum test at 10.5 kW discharge power into resistive load**



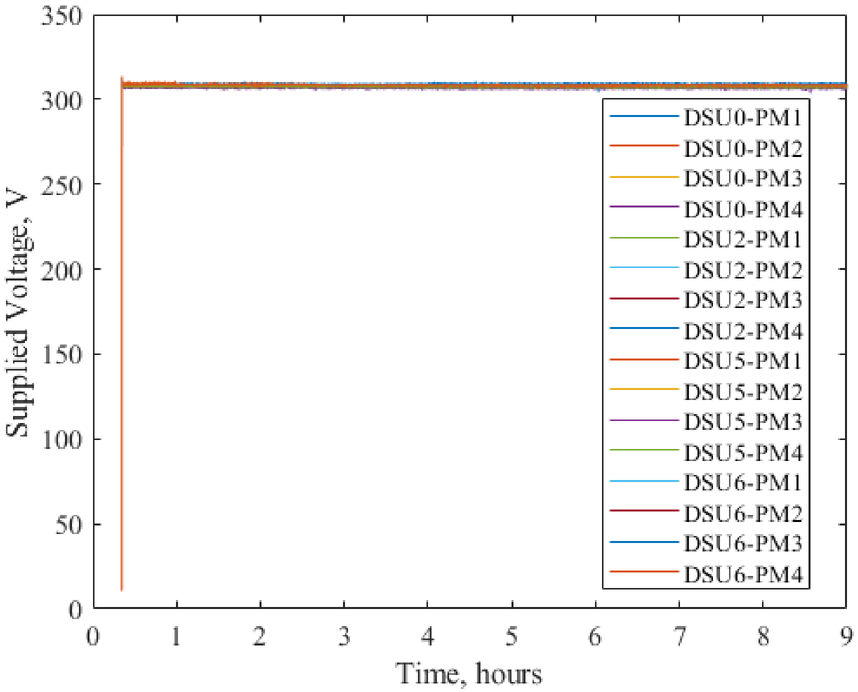
*Dark spot is obstruction in camera field of view

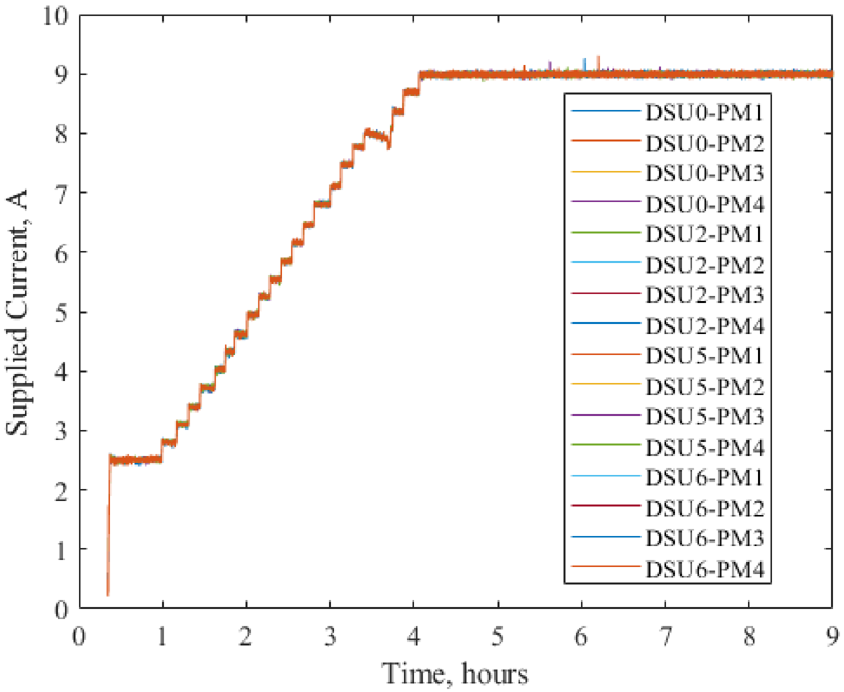
Thruster Behavior at 73.5 kW



Thermal equilibrium reached after dwell at 73.5 kW operating point

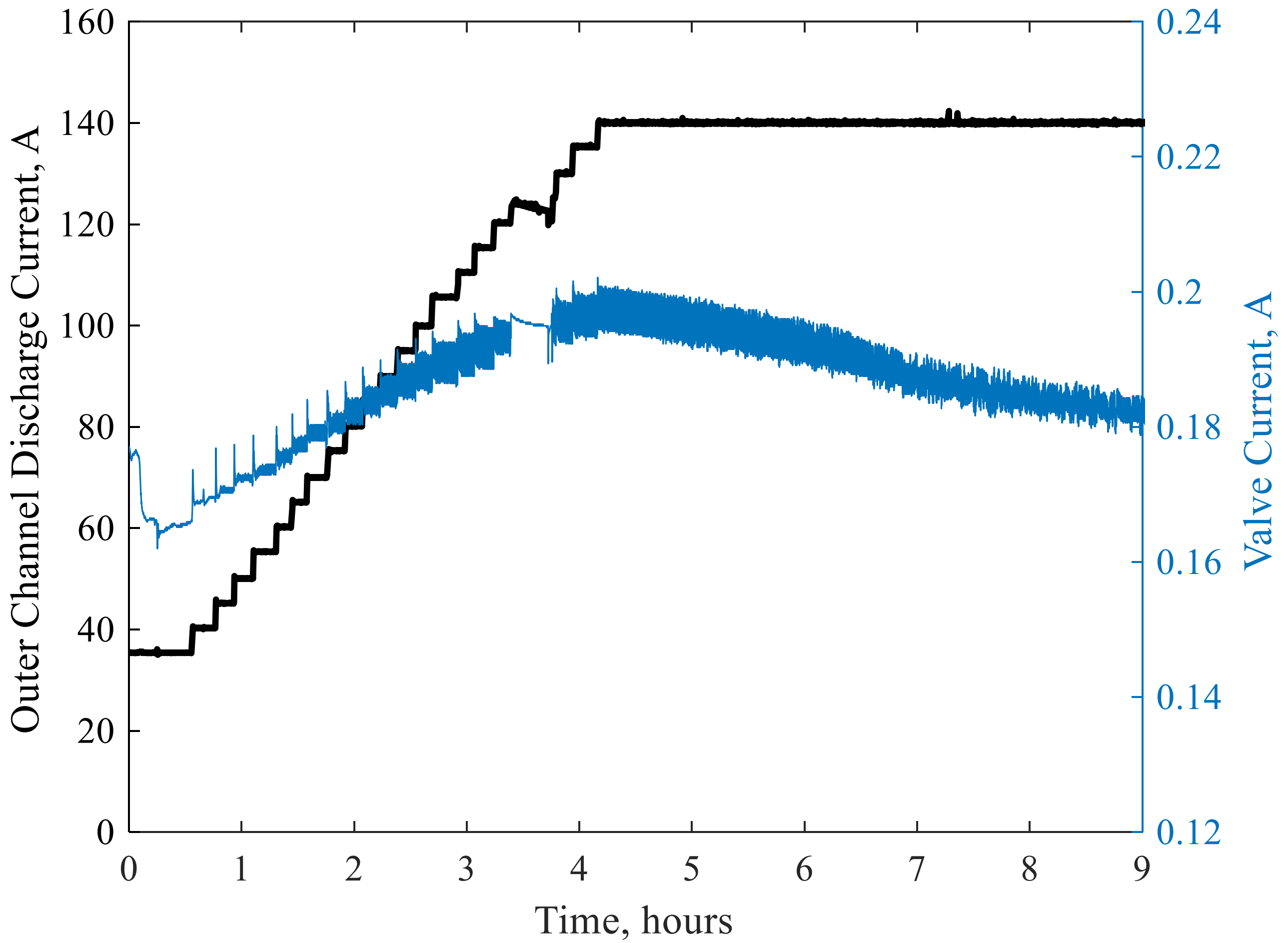
PPU Performance





Distributed Load Across All Outer Channel Power Modules

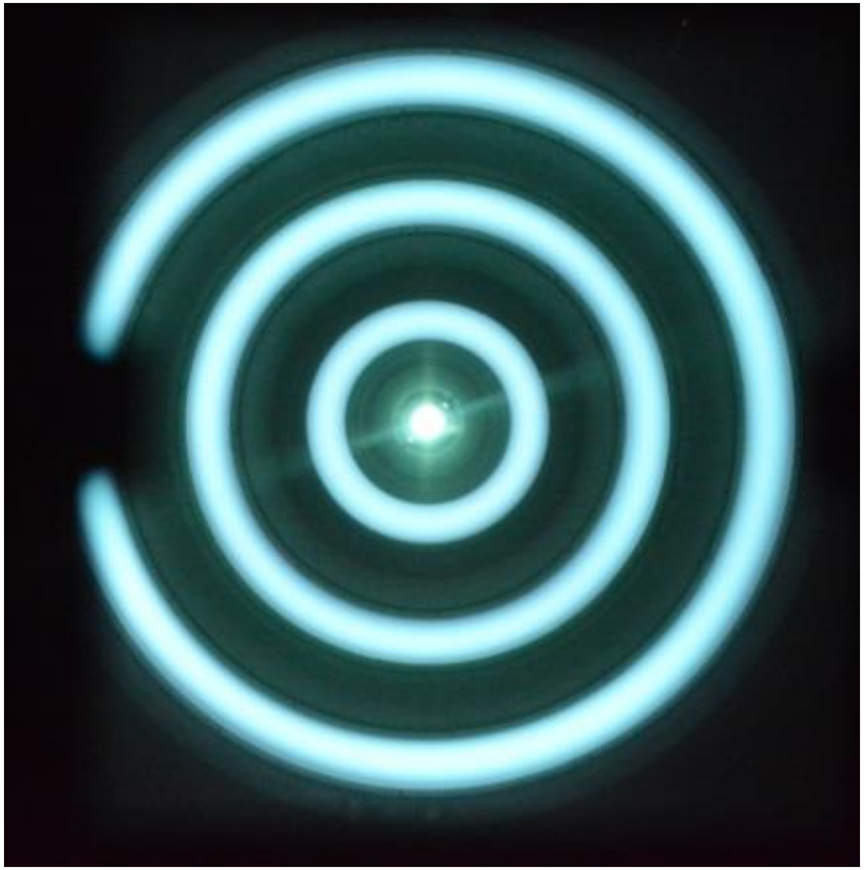
PPU Performance – Closed-Loop Current Control



Valve current constantly adjusted to maintain Discharge current

Three Channel XR-100 System Operation

- XR-100 system demonstrated electrically stable operation at >50 kW
  - 245 A due to facility limitations
    - Inner channel on 25 A limit lab power supply
    - Middle and Outer channels on DSUs
  - After demo at 300 V, increased voltage to increase power up to 100 kW
- Demonstrated 93 kW EP string operation at 350 V for short duration
  - System performance measured at 82.3 kW and 85.4 kW total
- High current event ended test campaign prior to thermal equilibrium



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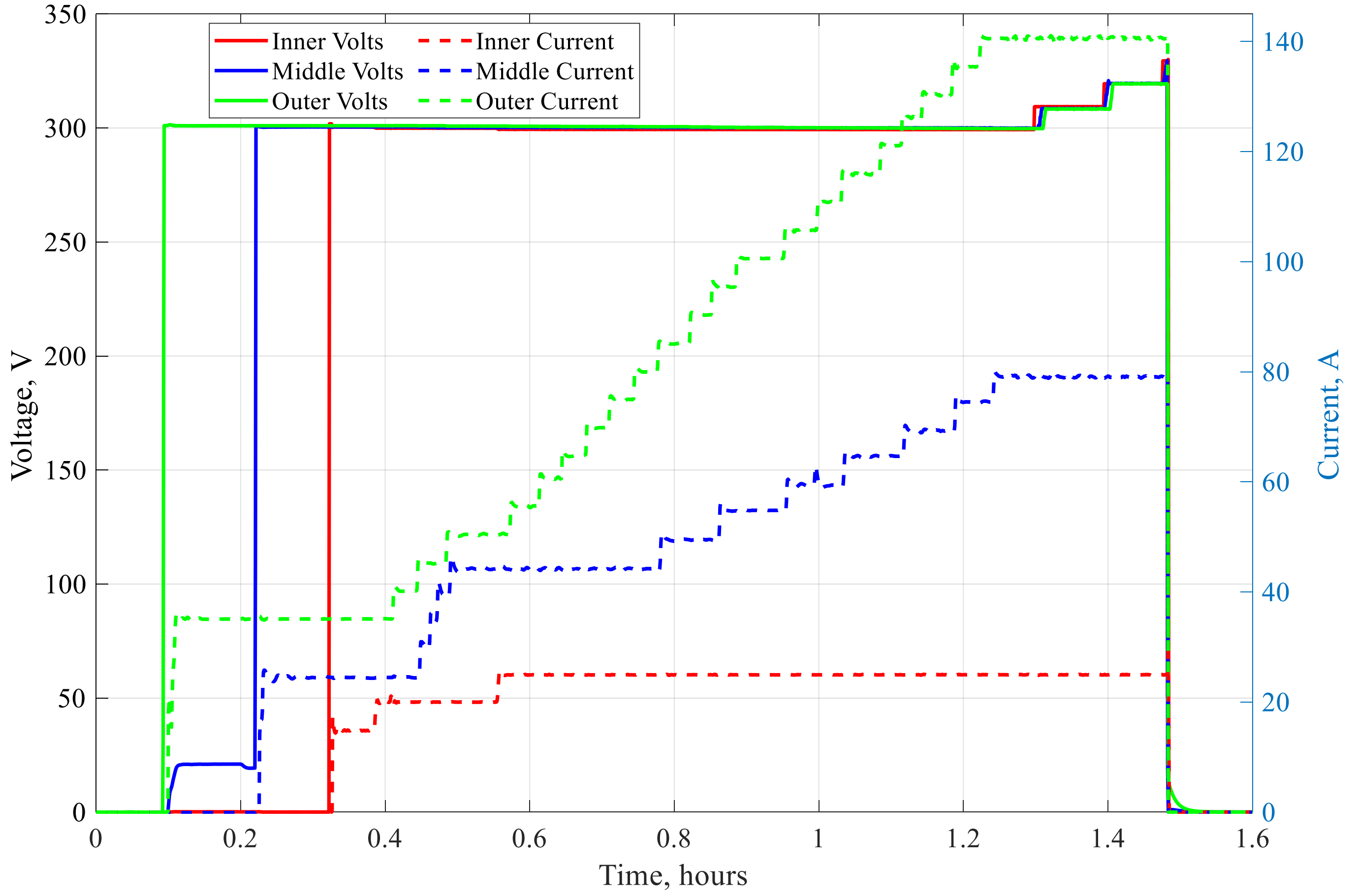
Three Channel XR-100 System Operation



Increased Discharge Voltage to Increase Power

XR-100 System Performance

Inner	Middle	Outer	Total Power	Thrust [mN]	Isp [s]	System Efficiency
-	300V/79.3A	301V/141A	73.7 kW	4100	1976	56.9%
-	300V/79A	300V/141A	73.7 kW	4080	1951	56.0%
299V/25A	300V/78.9A	300V/141A	80.1 kW	4574	1960	56.1%
309V/24.9A	308V/78.7A	308V/140A	82.3 kW	4600	1974	55.5%
319V/25A	320V/79.2A	319V/141A	85.4 kW	4658	2012	55.3%

System performance measured at high thrust, low efficiency case

Thruster vs System Performance

- Three channel system performance around 300 V and 75 kW discharge power compared to three channel thruster-only performance from 2017 testing (gray)

Inner	Middle	Outer	Discharge Power	Thrust [mN]	Isp [s]	T/P [mN/kW]
299V/25A	300V/78.9A	300V/141A	73.4 kW	4574	1960	62.0
298.4V/33.6A	300.1V/78.6A	298.1V/138.5A	74.9 kW	4640	2020	61.9
309V/24.9A	308V/78.7A	308V/140A	75.0 kW	4600	1974	60.5
319V/25A	320V/79.2A	319V/141A	78.3 kW	4658	2012	59.2

XR-100 system performance consistent with X3 NHT performance

Accomplishments

- Thermal equilibrium of the EP string at 73.5 kW total power
  - Highest power demonstration published to date
- Highest measured thrust of an EP string published to date
  - 4.1 N during two channel operation
  - 4.6 N during three channel operation with 7 DSUs and a lab power supply
- Highest current operation of an EP string published to date
  - 220 A during two channel operation
    - Highest current demonstration of a PPU
  - 245 A during three channel operation with 7 DSUs and a lab power supply

Forward Work

- Modification of the thruster magnetic circuit
  - Reduce thermal loading
  - Implement magnetic shielding
- Improve electrical isolation for thruster components
- Incorporate better heat transfer design within the DSU
- Modify DSU operating range to better align with NHT operating range
- Size PPU circuit components to withstand higher current events

Acknowledgements

- Aerojet Rocketdyne
  - Sam Hablitzel, Jerry Jackson, Brian Koch, John Pace, Aaron Poehls, Erich Soendker, Arturo Tolentino, and Benjamin Welander
- University of Michigan
  - Sarah Cusson, Marcel Georgin, Leanne Su, Joshua Woods
- NASA Glenn Research Center
  - James Gilland, Chad Joppeck, Thomas Liu, Eric Pencil, Taylor Varouh
  - All of the facility technicians at VF-5
- Jet Propulsion Laboratory
  - Alejandro Lopez Ortega, Ioannis Mikellides, and Sean Reilly
- Aerojet Rocketdyne Interns
  - Jordan Marshall, Samar Mathur, Alex Mundahl, Adam Patel, Nick Simon, and Henry Steiner

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